Fermilab

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LASER DIAGNOSTIC FOR ELECTRON COOLING BEAM

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Introduction

The design electron beam of $r = 2.5$ cm, $j_e = 1.5$ A/cm^2 will generate a profile potential depression of $\Delta v = \pi j_e r^2/\beta\gamma c$ = 1300 volts. If uncompensated, this implies a rest frame longitudinal temperature profile $\Delta T_{\parallel} \sim 7$ eV, as compared with $\Delta T_{\perp} \lesssim 0.5$ eV. Although $\bar{p}$ cooling would still occur, the damping time would be long compared with the booster cycle. For a highly neutralized beam, where $\Delta T_{\parallel} << \Delta T_{\perp}$, the damping time is dramatically reduced ($\propto \Delta v^{-1}$). Thus a well understood neutralization mechanism is essential for useful cooling and will require a powerful diagnostic monitor. The laser probe described is the only method we know of which can perform this monitoring at full D.C. beam current. In addition it can measure residual electron temperature by line broadening.

Optics Design

Geometrical constraint of the cooling section restricts us to $\approx$ forward/backward Thompson scattering of a laser on the beam. Backscatter is chosen to 1) take advantage of being "blue shifted" out of the thermal photon background domain and 2) be at the end of the drift region away from the cathode.

As indicated in Fig. A only about 3 m of the e^- beam is a useful source. Assuming 1 m from beam bend to an optics vacuum port, a laser focus lens of F.L. = 1 m + 3 m/2 = 2.5 m is needed.

With available TEM_{∞} mode lasers at 1.06μ, this sets a maximum spot size in the scattering region of:

$$w = \sqrt{(F.L.)\cdot\lambda/2\pi \ \left(1+ (3m/F.L./2)^2\right)} = 0.07 \text{ cm}$$

which determines a radial resolution $w/r = 2.8 \times 10^{-2}$.

Now let:

p = electron momentum

ω_o = laser frequency (λ_o = 10630 Å)

ω = backscattered frequency.

Then $\frac{\omega}{\omega_o} = \frac{1+\beta}{1-\beta} = 3.61 \qquad (\beta = 0.566)$

giving us ultraviolet backscatter at λ = 2950 Å .

For exact backscatter:

$$p/\omega \frac{\partial\omega}{\partial p} = \frac{\beta}{(1+\beta^2\gamma^2)(1-\beta^2)} = 1.14$$

and, relating potential profile Δv of the e^- beam to ∂p,

$$\frac{\Delta\lambda}{\lambda} = (1.14)\ \Delta v\ (\beta^2\gamma m_c)^{-1}$$

$$= 7.4 \times 10^{-3} \text{ for } \Delta v = 1300 \text{ v}$$

or $= (w/r)\ 7.4 \times 10^{-3} = 2.1 \times 10^{-4}$ as a resolution limit.

Thus we need an optical analyser capable of resolving $\Delta\lambda$ = 2950Å x 2.1×10^{-4} = 0.6Å and having a one order range ≃ 20Å. This is a very <u>low</u> resolution job for a Fabrey-Perot interferometer,[1] which happens also to have the highest luminosity of any optical spectrum analyser.

We must collect the backscatter in a cone of limited $d\Omega$, commensurate with the above resolution. Figure B describes this constraint. We have

$$\frac{\Delta\lambda(\text{within cone } \Delta\theta)}{\lambda} = 0.66\ (\Delta\theta)^2 \quad .$$

If, as a minimum, the collecting aperture is no wider than the beam, then $R_{coll.} \gtrsim 200$ cm in order to preserve the 0.6Å resolution.

Rate

Based on the Thompson formula we have:

$$R = R_\gamma\ (n_e L/\gamma)\ \left(\frac{d\sigma}{d\Omega}\right)_{rest}\ \frac{d\Omega_{rest}}{d\Omega_{Lab}}\ (d\Omega_{Lab})$$

$$R_\gamma = \text{photons/s in laser} = (0.51 \times 10^{15}) \cdot P(w) \cdot \lambda(\text{Å})$$

$$n_c = \text{beam } e^- \text{ density} = 5.5 \times 10^8/\text{cm}^3$$

$$\left(\frac{d\sigma}{d\Omega}\right)_R = \text{Thompson cross s} = \frac{1}{2}\ (2.8 \times 10^{-13}\text{cm})^2 (\vec{\varepsilon}_i \cdot \vec{\varepsilon}_o)^2$$

$$\frac{d\Omega_R}{d\Omega_L} = 1/\gamma^2 \ .$$

Using the above aperture constraints:

$$\langle L d\Omega_L \rangle = \int_{200\text{ cm}}^{700\text{ cm}} dR \quad \frac{\pi 3^2}{R^2} = 0.13 \text{ cm} \ .$$

We have then:

$$R = (5.9 \times 10^{18}\ \gamma/\text{s})(5.5 \times 10^8/\text{cm}^3)(3.9 \times 10^{-26}\text{cm}^2)(0.67)(0.13\text{ cm})$$

$$= 32\ \gamma/\text{s}$$

This is for a 14 watt average power Nd laser (typical commercial unit - TEM_{∞}). The specific proposed instrument (Fig. C) will have a net collection efficiency of ~20%. Phototube efficiencies at this wave length are ~30%. Thus we expect ~14 signal count/s.

Background

The general method proposed here has been successfully used for years as a plasma diagnostic,[2] where high resolution has been obtained with scattered light only a few Å from the laser line. We follow the same design precautions of collimation and filtering. Considering the advantage in blue shift we enjoy (compared to the situation with plasmas), it is safe to conclude that there will be no effective laser induced background.

Recombination and excitation background due to the e^- beam (acting on gas) should prove to be no larger a percentage background than a luminous high temperature plasma has.[3] Hydrogen has no transitions near 2950 Å. Nitrogen or Oxygen may contribute interfering radiation. Their ionization cross sections have been measured,[4] and any excitations to discrete levels can be considered negligible. Assuming an equilibrium where the recombination rate equals the ionization rate for complete neutralization gives:

$$\sigma_{ion}\ (O_2 \text{ or } N_2) \sim 1/2 \times 10^{-16}\ \text{cm}^2$$

$$N = \#\ \text{target atoms} = 5 \times 10^8/\text{cm}^3 \cdot 500\text{cm} \cdot 30\text{cm}^2$$

$$R_c \equiv \text{Bombardment Rate} = 25\ \text{Amp}/1.6 \times 10^{-19}\text{C}$$

$$R_c = \text{total Recombination Rate} = \frac{1\ \text{KeV}}{120\ \text{KeV}} \cdot \sigma_{ion} \cdot R_e \cdot N/30\ \text{cm}^2$$
$$= 1 \times 10^{14}/\text{s}$$
$$R_c \times \text{Duty Factor} \times d\Omega = 1 \times 10^{14}/\text{s} \cdot 10^{-4} \cdot 10^{-4} = 1 \times 10^{6}/\text{s}$$
$$\times \%\ (O_2 + N_2) = 5 \times 10^{4}/\text{s}$$
$$\times \text{transition probability} \approx \boxed{10/\text{s}}$$

This is only meant to give an idea of the quantities involved. Actually the recombination rate is expected to be much less than the ionization rate. Ions will be trapped in an electrostatic well so that H^+ will eventually dominate (since multiply ionizing atoms will be first expelled) and electrons will be ejected along the beam axis.

Bremsstrahlung (e^- - ion) is also expected to be small:

$$\sigma_B(\omega) \sim \frac{1}{\hbar\omega} \frac{16}{3} \beta^2 \ r_o^2 \ \alpha \ \ell n \left(\frac{mv^2}{\hbar\omega}\right)$$
$$\simeq 10^{-26}\text{cm}^2$$

$$\therefore R_B, \text{ of photons @ } \omega \approx \sigma_B(\omega) \cdot R_c \cdot N/30\text{cm}^2$$
$$= 2 \times 10^{6}/\text{s}$$

which gives in this apparatus:

$$R_B \cdot (\text{duty factor}) \cdot d\Omega \cdot \frac{d\lambda}{\lambda} \simeq (2 \times 10^{6}/\text{s})\ (10^{-4}) \cdot (10^{-4}) \cdot (2 \times 10^{-4}) = 10^{-3}/\text{s}.$$

Black body radiation from the cathode is expected to be the worst background. The power radiated per spectral interval is:

$$\delta P = (5.7 \times 10^{-8})(\text{Area})\ \frac{15}{\pi^4}\ \frac{X^4}{e^X - 1}\ \left(\frac{dX}{X}\right)\ (T_{^\circ K})^4$$

with $$X = \frac{hc}{\lambda KT} = 38.1$$

for a 1000° C cathode at 2900 Å.

For our cathode and using the previously discussed resolution window:

$$\delta P = 3.8 \times 10^{-12} \text{ watt}$$

$$= 5.7 \times 10^{6}\ \gamma/s\ .$$

This will be reduced by:

1) The detector subtends only ~5 cm at an equivalent distance of ~900 cm from the cathode => P_{det}/P_{cath} $\sim (5/900)^2 \lesssim 10^{-4}$.

2) The cooling section geometry is such that all rays entering the collected backscatter cone suffer at least two $\measuredangle I = \measuredangle R$ reflections on walls, etc.

3) The laser duty factor will be $10^{-3} - 10^{-4}$.

The photomultiplier (RCA C31000), when cooled will have a dark count rate of ~100/s; well below the pulse gated signal rate.

It is interesting to note that the very first demonstration (shortly after the invention of the first ruby laser!) of laser-electron Thompson scattering involved the blue shift of laser light scattered from an electron beam of density equal to ours.[5]

Other Possibilities

We recognize the difficulty of using a diagnostic supplying a few photon/s signal. Present technology can supply higher power lasers of comparable beam quality, but an order of magnitude increase in sophistication and cost would be needed for such a brute force approach. We have based our estimates here on standard single rod devices.

It is feasible to have the electron beam-laser interaction region be <u>inter</u> cavity. A scheme similar to the ADONE laser-gamma beam is quite possible.[6] This would be at the expense of greatly increased complexity of the in vacuum optical system.

References

1. M. Born, E. Wolf, Principles of Optics, 3rd edition.
2. For a thorough discussion of laser plasma diagnostics see the review by D. Evans and J. Katzensten, Rep. Prog. Phys., 32, 207 (1969).
3. A particularly relevant plasma diagnostic technique. For our case (C. W. Plasma at low density and low electron temperature) is described in: L. Koons, G. Fiocco, J. Appl. Phys., 39, 3389 (1968).
4. E. W. McDaniel, Collision Phenomena in Ionized Gases, John Wiley, 1974.
5. G. Fiocco, E. Thompson, Phys. Rev. Lett. 10, 89 (1963).
6. R. Caloi, et al., Laser Light Against High Energy Electron Scattering. LNF-76/31(R).

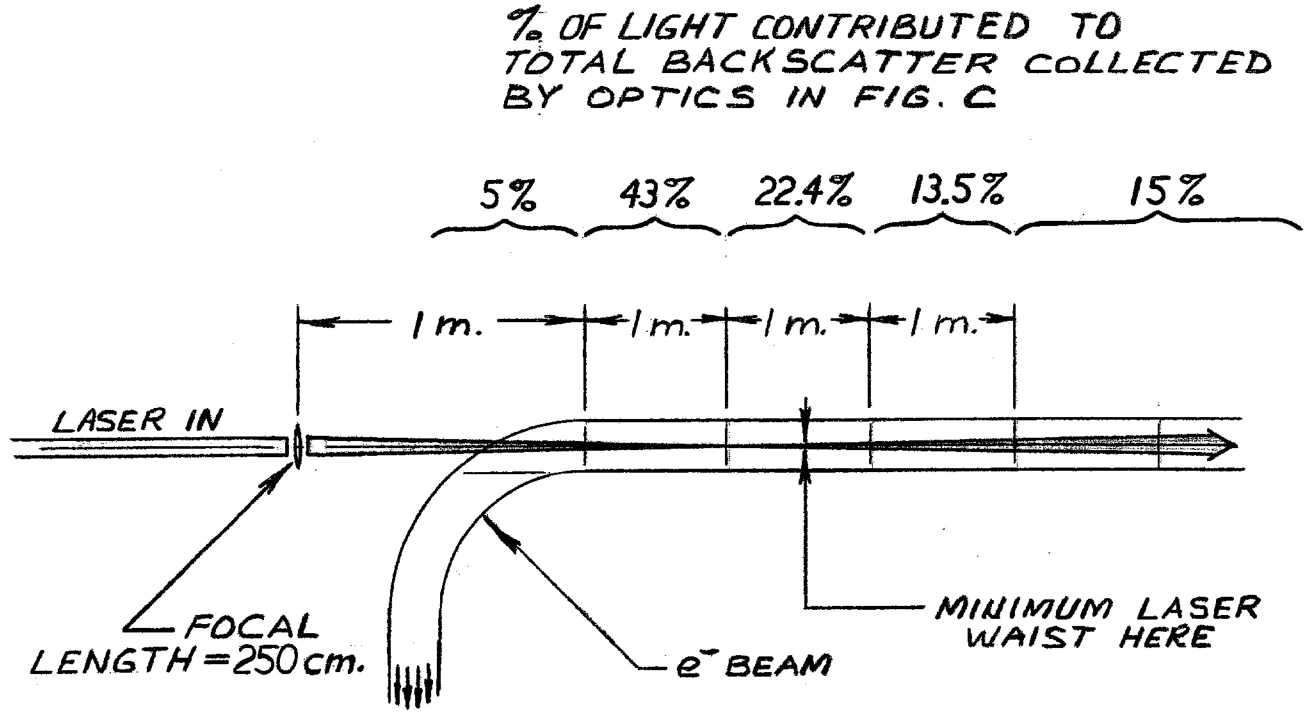
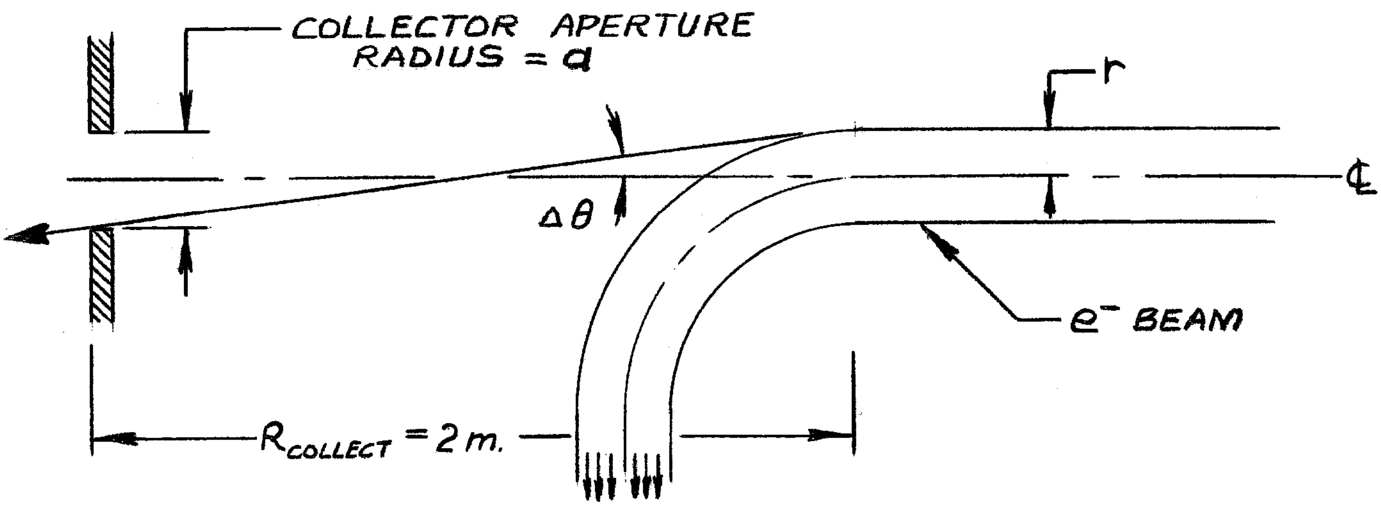


FIG. A

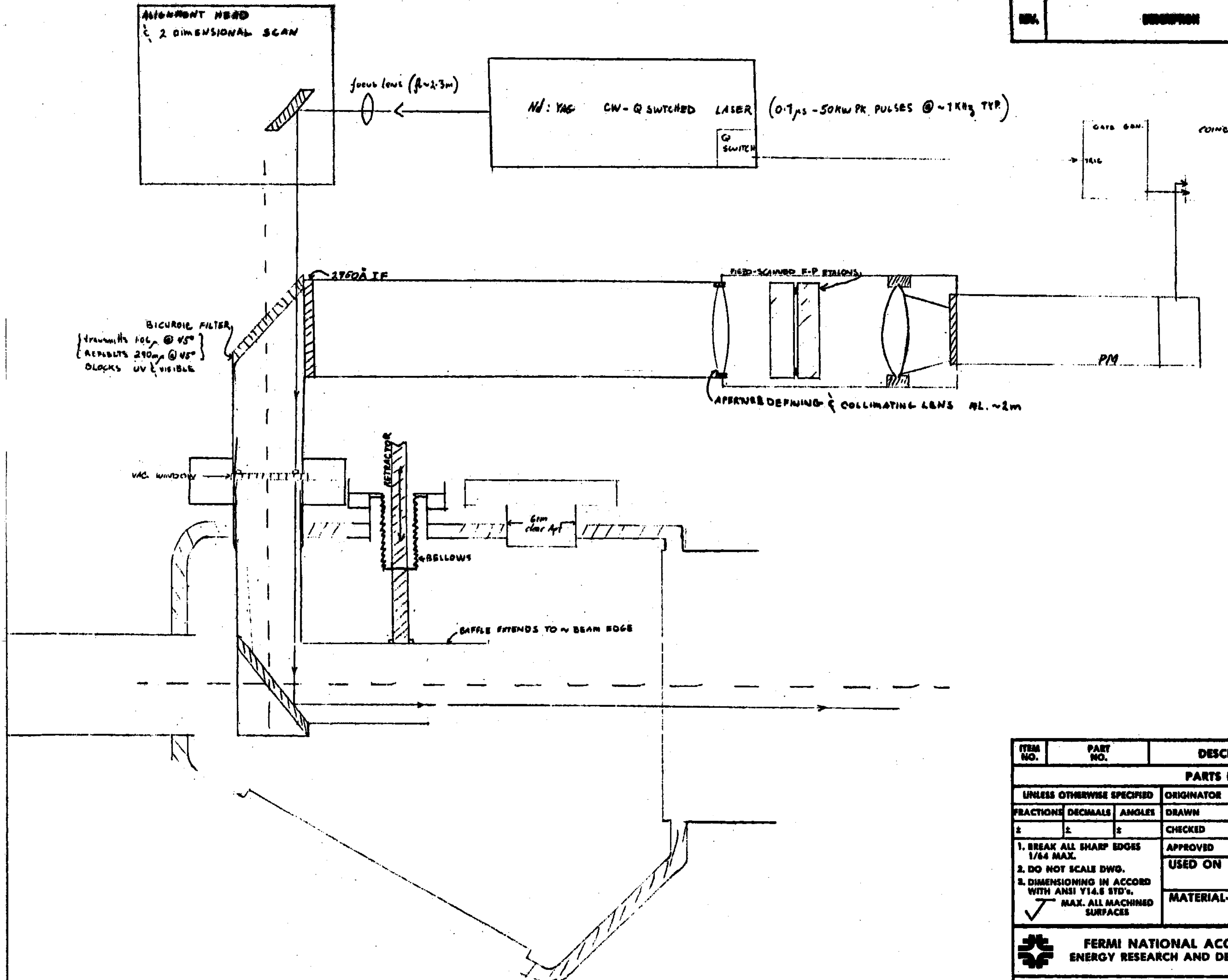


$$\Delta\theta = \frac{r+a}{2\text{ m.}} = \frac{0.05}{2\text{ m.}}$$

$$\frac{\Delta\lambda\,(\text{in } \Delta\theta \text{ cone})}{\lambda} = \frac{\beta}{2(1-\beta)}(\Delta\theta)^2$$

FIG. B

REV.	DESCRIPTION	DRAWN	
		APPD.	



ITEM NO.	PART NO.	DESCRIPTION OR SIZE	QTY. REQ.

PARTS LIST

UNLESS OTHERWISE SPECIFIED			ORIGINATOR	W. Kells	1/16/78
FRACTIONS	DECIMALS	ANGLES	DRAWN	W. Kells	
±	±	±	CHECKED		
			APPROVED		

1. BREAK ALL SHARP EDGES 1/64 MAX.
2. DO NOT SCALE DWG.
3. DIMENSIONING IN ACCORD WITH ANSI Y14.5 STD's.
√ MAX. ALL MACHINED SURFACES

USED ON

MATERIAL-

FERMI NATIONAL ACCELERATOR LABORATORY
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

SCALE	FILMED	DRAWING NUMBER	REV.
1/2			